

Fabrication of Stable, Large-Area, Thin-Film CdTe Photovoltaic Modules

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ABSTRACT

Solar Cells, Inc (SCI) has a program to produce 60 cm X 120 cm solar modules based on CdTe films. The method of choice for semiconductor deposition is condensation from high temperature vapors. Early work focussed on Close Spaced Sublimation and Chemical Vapor Deposition using elemental sources, but later equipment designs no longer strictly conform to either category. Small area efficiency has been confirmed by NREL at 9.3% on a 0.22 cm² device (825 mV Voc, 18.2 mA/cm² Jsc, and 0.62 FF) deposited on a 100 cm² substrate. On 8 cell, 64 cm² submodules, the best result to date is 7.3% (5.9 V Voc, 130 mA Isc, and 0.61 FF). CdS, CdTe, and ZnTe films have been deposited onto 60 cm X 120 cm substrates - single cells produced from this material have exceeded 8% efficiency, 64 cm² submodules have exceeded 5%. Module efficiency is limited by mechanical defects - mostly shunts - associated with processing after deposition of the semiconductor layers. Present best result is 1.4% total area efficiency. In anticipation of more advanced designs, CdTe films have also been deposited from apparatus employing elemental sources. This project is in an early stage and has produced only rudimentary results. A pro-active Safety, Health, Environmental and Disposal program has been developed. Results to date indicate that both employees and the environment have been protected against overexposure to hazards including toxic chemicals.

I INTRODUCTION

SCI was formed in 1987 to be a vertically integrated manufacturer of multi-megawatt solar electric generating fields. Manufacturing of thin film photovoltaic modules is one part of this mission. In late 1990, SCI began a program to investigate the viability of producing these modules using CdTe based films deposited from elemental vapors onto high temperature superstrates. CdTe was selected as the principal semiconductor layer due to its record of high efficiency and device stability, and its flexibility with respect to its method of deposition [1]. This flexibility allows SCI the freedom to independently choose a manufacturing method based on attributes of low cost, high throughput, and reliability, and then to adapt that process to the deposition of CdTe based photovoltaic films. Close spaced sublimation (CSS) was chosen due to its high deposition rate and its demonstrated capability to produce state of the art efficiency devices [2-5].

Earlier work on CSS [2-5] had produced devices using a static deposition chamber - no moving parts. Typical CSS deposition apparatus consists of a source of semiconductor material - either in powder or crystalline form - separated from a glass superstrate by fixed spacers. See Fig. 1. The entire apparatus is enclosed in a quartz vessel so that the deposition can occur under conditions of controlled pressure and ambient gas. The source and superstrate can be heated independently - typically using quartz lamps external to the quartz vessel.

Equipment designed and built at SCI has incorporated certain features of CSS into its deposition apparatuses. Two of the three deposition systems utilize sublimation of powders to create the hot source gasses; all systems utilize high temperature superstrates. The third piece of deposition apparatus utilizes elemental sources to produce the source vapors. This allows further latitude in the design of the final manufacturing process.

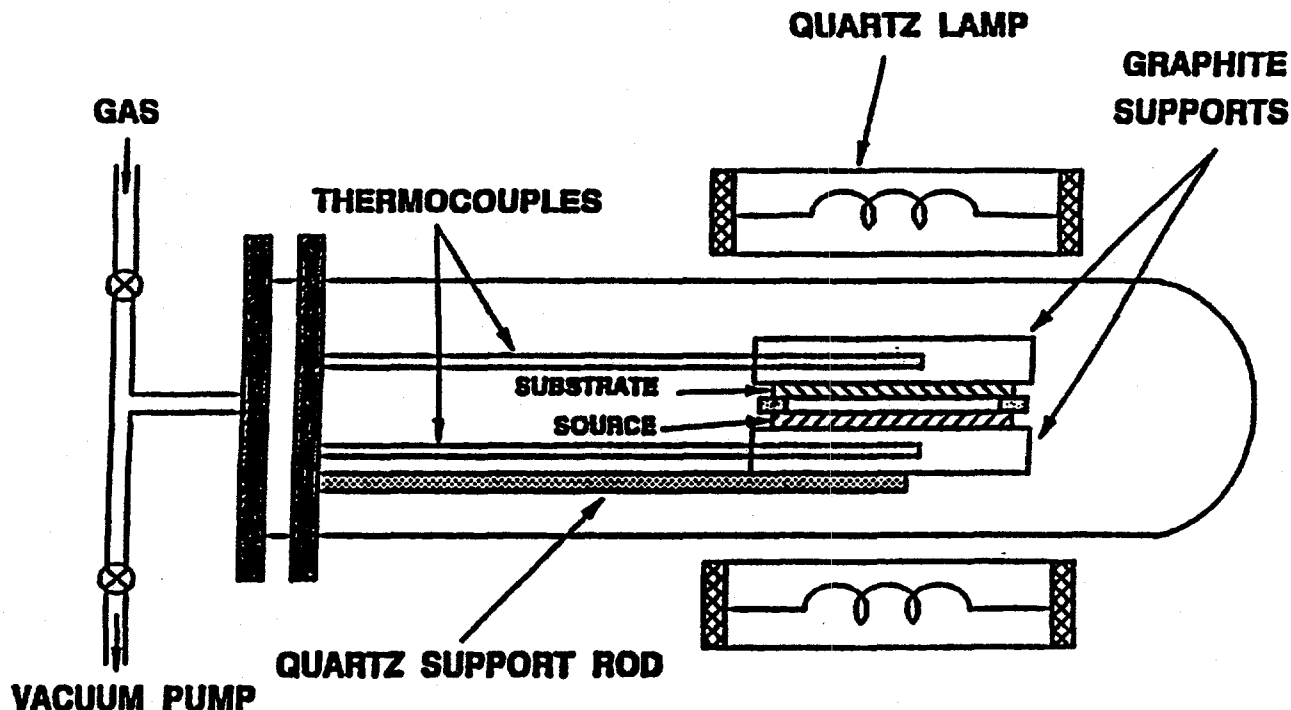


FIGURE 1

Prior Art - Close Spaced Sublimation.

II RESEARCH SCALE DEVICES

A) Deposition Apparatus

Small devices are defined as those produced on 100 cm^2 superstrates. The semiconductor layers are deposited in an apparatus called the RMS, for Research - Multi-Stage. The main chamber is constructed of stainless steel with internal dimensions of approximately $5' \times 9' \times 1'$. It can be pumped by either a mechanical fore pump or a $10''$ turbopump; the later enables the system to attain background pressures below 10^{-6} torr. Samples enter and exit the chamber through a separately pumped loadlock with approximate dimensions of $2' \times 1' \times 1'$.

As can be seen in Fig. 2, the samples enter the chamber at one end of a corridor. The actual deposition occurs in separate zones located to one side of the main passageway. The system is designed so that a variety of films can be deposited in sequence. Thus, one chamber is used to preheat the glass superstrate, a second to deposit CdS, a third to deposit CdTe, a fourth to deposit ZnTe, and a fifth to cool the superstrate with its composite films.

The source materials are held in an $11.5 \text{ cm} \times 11.5 \text{ cm}$ boat approximately 3 mm deep. The boat is heated by a radiant heater located below the boat. Maximum boat temperature - which was limited by the capacity of the heater - is about 760°C . The temperature of the glass superstrate was monitored by two thermocouples in loose physical contact with the glass on the side opposite the deposition; temperature variation across the glass superstrate, as measured in this manner, is typically less than 20°C .

a) RESEARCH MULTI-STAGE DEPOSITION SYSTEM

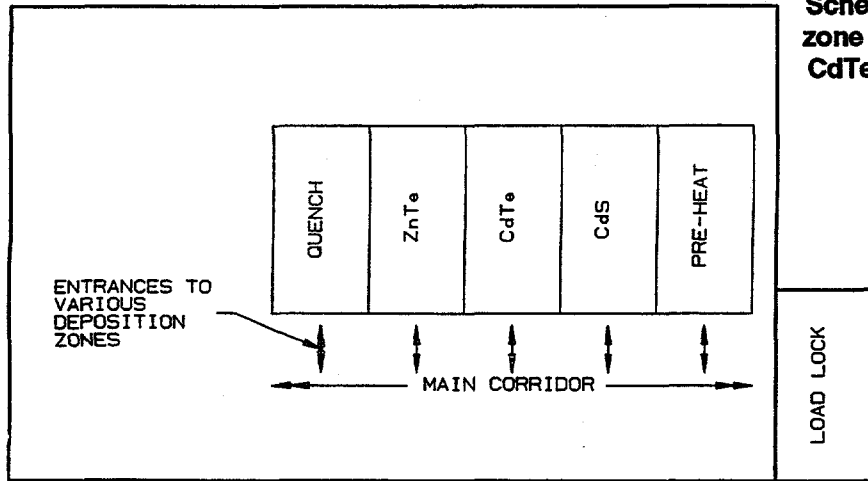
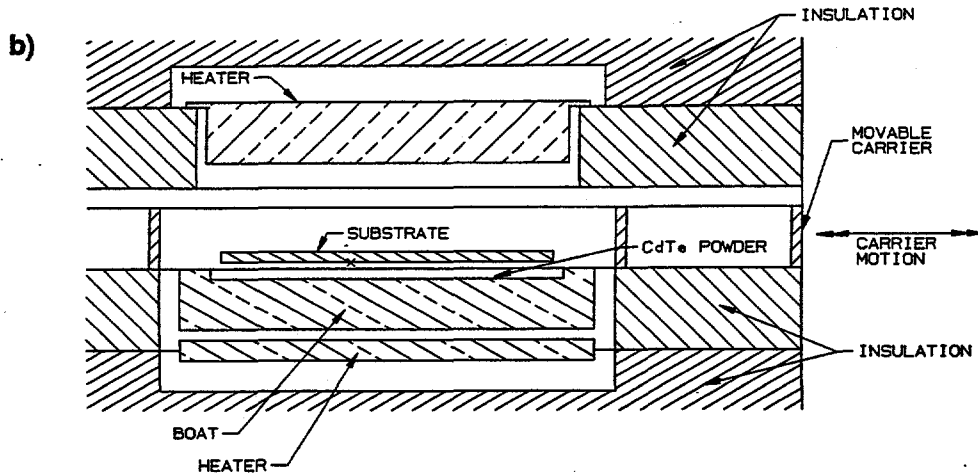


FIGURE 2
Schematic views of RMS system: (a) zone layout, and (b) cross section of CdTe deposition zone.



It is worth noting that the principal functional difference between the SCI deposition chamber and others described in the literature is that this chamber allows for the insertion and removal of the superstrate from the deposition zone whereas deposition chambers employed in earlier work required that the source and superstrate remain in close, fixed position during the heating, deposition and cooling stages of the process. This feature not only more closely simulates deposition in a production environment, but also enables a greater degree of independence of the deposition variables, and enables the deposition of multiple films without removal from the chamber.

1. Glass Cleaning

The majority of depositions have been on 5 mm SnO₂:F coated glass obtained from LOF. Prior to deposition, the glass must be cleaned. An experimental series of depositions was conducted in order to determine the sensitivity of properties of CdTe films as deposited in the

RMS chamber process to superstrate preparation. In particular, we were interested determining conditions which would minimize the number of pinholes. Several superstrates of 7.5, 10, and 20 Ω /sq LOF SnO₂:F coated glass were prepared by each of the following procedures:

- * clean in a pH 13 detergent
- * buff with CeO prior to cleaning in pH 13 detergent
- * clean in a pH 13 detergent, then dipped in 2% HF and DI H₂O rinse
- * clean in a pH 13 detergent, then soaked for 3 minutes in 2% HF and DI H₂O rinse
- * clean with methanol only
- * clean with Alconox, then DI H₂O rinse
- * clean with a pH 13 detergent, then coated with a thin film of CdS.

CdTe films were deposited under conditions which had produced poor quality films in the past - ambient pressure of 0.1 torr N₂ and 690°C boat temperature. The pinhole density on each film was measured and the uniformity assessed. Films deposited on CeO buffed superstrates or on CdS films were more uniform and almost pinhole free. As CdS is required to make efficient devices, the typical cleaning procedure employed in deposition of CdTe films employs cleaning in a pH 13 detergent.

In addition to providing useful information on the effects of film cleaning, this study points up the dependence of film properties on superstrate conditions. That is, since one film property - pinhole density - is sensitive to the superstrate conditions, we have less confidence that other properties - grain size, conductivity, defect level concentrations - will be independent of the superstrate. Thus properties of individual films provide hints as to the optimum deposition parameters, but only fabrication of devices provides definitive data.

2. SnO₂ Conductivity

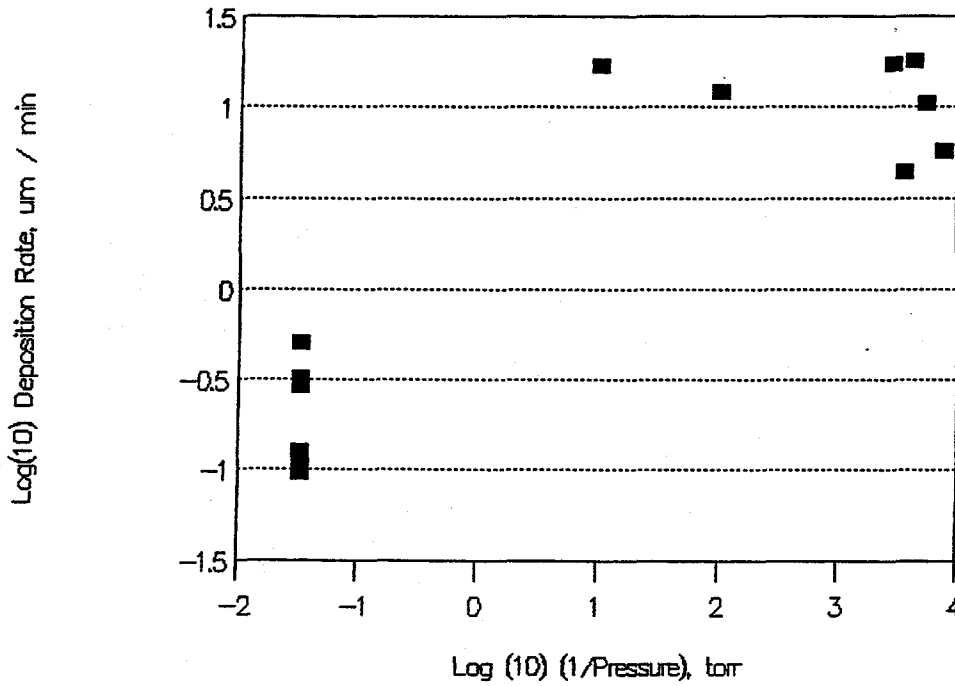
The ambient during deposition of the films - temperature ~600°C in vacuum or oxygen-free environment - can have the effect of increasing the resistance of the SnO₂:F coating on the superstrate. Films heated to ~600°C in vacuum exhibit a threefold increase in resistivity; upon reheating in air at the same temperature, however, the resistivity can be restored almost to its original value. Hall measurements performed by Randy Bohn at UT show that this is attributable to changes in the mobility of carriers; mobility decreased from 30 to 10 cm²/Vs after the vacuum heat treatment. The probable mechanism is an increase in scattering by oxygen vacancies at grain boundaries. Measurements made after semiconductor deposition and device fabrication indicate that SnO₂:F sheet resistance is typically 30% higher than its original value.

3. CdTe Deposition

The source material is typically 4.5N's CdTe powder obtained from ASARCO. Films were deposited with source temperatures in the range of 700-740°C, in an N₂ ambient, with background pressures in the range of 10⁻⁴ to 30 torr, and with superstrate temperatures ranging from 485-575°C. Deposition rates up to 18 μ m/min were obtained at the lower pressure ranges. Films as thick as 44 μ m (600 s) were deposited. The results are qualitatively similar to those obtained by researchers at Stanford - those data are included for comparison. See Fig. 3.

Deposition Rate Log ($\mu\text{m} / \text{min}$)

(a) SCI



(b) Stanford

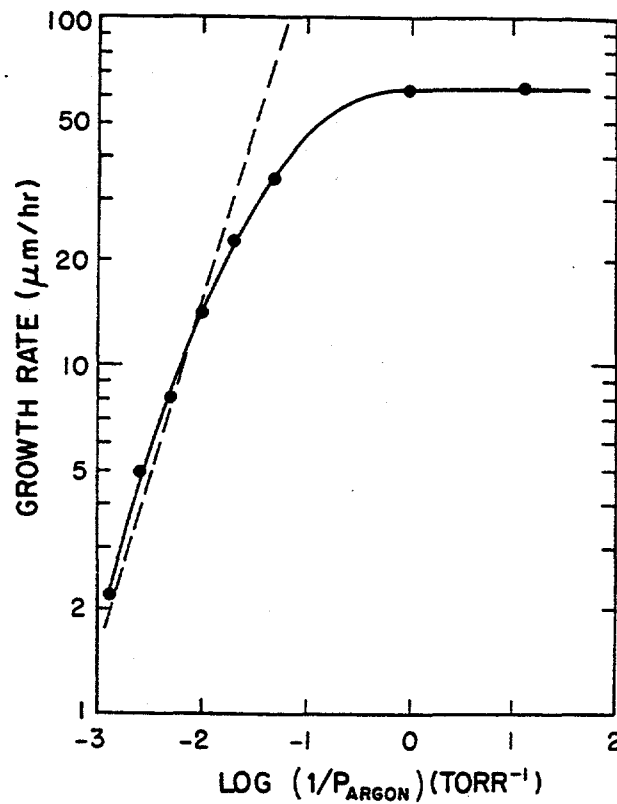


FIGURE 3

Comparison between deposition rates observed (a) at SCI in an N_2 ambient, and (b) at Stanford in an Ar ambient. The theoretical diffusion limited growth is indicated by the dashed line [5].

The SEM photos indicate that the grain size for the thinner films is a fraction of a micron, but may be 1 μm or larger in the thicker films. See Fig. 4. The transmission spectra clearly exhibit the CdTe absorption edge, but also indicate poor subbandgap transmission - typically 15%.

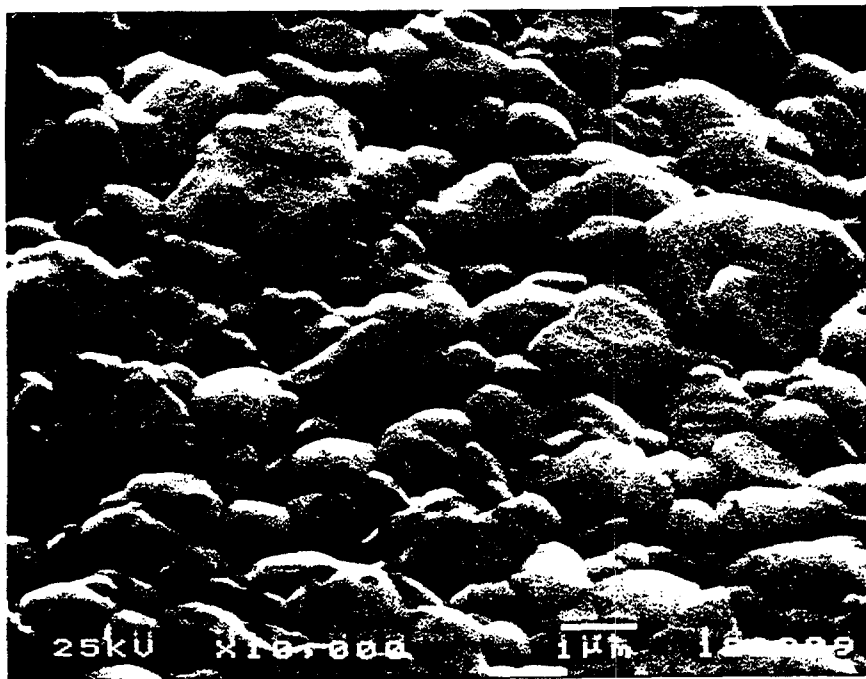


FIGURE 4
Micrograph of as-deposited CdTe on CdS film.

XRD measurements performed at IEC revealed that the as-deposited films exhibit a strong (220) orientation. After the CdCl_2 HT, however, the (111) peak is greatly enhanced. Bob Birkmire speculates that the (220) orientation may be related to the high temperature ($T_{\text{sub}} > 350^\circ\text{C}$) deposition.

In collaborative work with NREL, samples were sent to Dick Ahrenkiel for photoluminescence lifetime measurements. In heat treated samples (discussed below), lifetimes approaching 1 ns were observed. It is my understanding that these lifetimes are characteristic of films which can be processed into ~12% efficient cells.

4. CdS Deposition

The source material was 4N's CdS powder obtained from ASARCO. Films were deposited with source temperatures in the range of 690-730 $^\circ\text{C}$, in an N_2 ambient, in a pressure range of 10^{-4} to 30 torr, for deposition times ranging from 20-120 s, and with a source - superstrate spacing of 0.3 cm. Typical glass superstrate temperature was 575 $^\circ\text{C}$.

Films appear visually to be of good quality and exhibit outstanding adhesion and resistance to chemical etchants. Thickness, as determined on a profilometer, varies up to several thousand angstroms. Uniformity is similar to that observed for the CdTe films.

5. ZnTe Deposition

Several attempts to deposit ZnTe:Cu films were made. The source material, prepared by ASARCO, was 4N's ZnTe with 1% Cu. Cells incorporating the ZnTe layer exhibit low efficiency as well as high internal resistance or a blocking diode internal to the cells. The latter is manifested by a characteristic "S-curve" - a bending over of the I-V curve in the first quadrant. We require Cu doped films to have bulk resistivity close to $1 \Omega\text{-cm}$. Measured resistivity on ZnTe films deposited in our plant is typically $10^5 \Omega\text{-cm}$. It appears that doped ZnTe:Cu does not sublime congruently. We can say for certain that the Cu from the doped source material is not transferred to the superstrate in its concentration in the powder. According to the literature and consistent with past experience, there is no question that ZnTe can be made more conductive by doping with Cu, Sb, or As.

In one attempt to address this problem, ZnTe films were deposited from a ZnTe:Sb(1%) source supplied by ASARCO. As was the case with films deposited from the copper doped material, these films have a resistivity on the order of $10^5 \Omega\text{-cm}$. In another attempt, an experiment was conducted using mixed ZnTe and Sb powders as source material for CSS deposition of films. Although somewhat simplistic in concept, it was hoped that this experiment would provide some insight into methods for producing doped ZnTe layers. A series of depositions were made onto glass superstrates at 480°C at successively increasing source temperatures. The results suggest that Sb films could be deposited from sources heated to $\sim 680^\circ\text{C}$, but this source temperature is too low to deposit ZnTe films which require a temperature of at least 715°C . All ZnTe films produced had bulk conductivities in excess of $10^6 \Omega\text{-cm}$.

Continuing our efforts to produce low resistivity ZnTe films, an experiment was conducted using ZnTe which we had doped in-house with Sb. Similar to procedures followed earlier, a series of depositions were made onto glass superstrates at 480°C at successively increasing source temperatures. The results were similar to those achieved earlier when ZnTe + Sb powders were used as the source material. Further work is required in this area.

B) Cells

1. Fabrication Procedures

A typical deposition sequence is as follows: A 5 mm sheet of commercially available $\text{SnO}_2\text{:F}$ coated soda lime glass is cleaned and placed into the RMS load lock. The glass is loaded with the SnO_2 coated surface downward. After the ambient gas in the load lock is adjusted to that of the chamber, the superstrate is inserted into the preheat station where it is heated to approximately 590°C . The superstrate is moved into the CdS deposition zone. The CdS is in an open faced boat so that deposition occurs upward to the lower (SnO_2 coated) surface of the superstrate. The CdS is kept at about 750°C ; deposition ambient is 0.1 torr N_2 . The source-superstrate spacing is ~ 3 mm; time to deposit $\sim 3000 \text{ \AA}$ CdS is approximately 20 s. The superstrate is then moved to the CdTe deposition zone. With a CdTe source temperature of 725°C , time to deposit a $3 \mu\text{m}$ film is about 30 s. If a ZnTe film is to be deposited, the superstrate would now be inserted into that zone. ZnTe deposition parameters are similar to those of CdS. After deposition of the semiconductor films, the multi-coated glass superstrate is taken over to the quench station where it is cooled by a stream of N_2 gas. At the end of a 10

second quench the measured glass temperature is below 300°C. The sample is then removed to the load lock chamber where it cools slowly to room temperature. Thus, once the glass has been heated - about ten minutes, total deposition time is less than one minute.

All films deposited in this manner appear to be densely packed and stoichiometric. Typical CdTe grain size is 1-3 μm . Adhesion, as measured with a force gauge and using tape pulled from the surface, exceeds 40 oz-in.

The most efficient devices produced to date were produced from CdTe/CdS films. These semiconductor layers were coated with a saturated solution of CdCl_2 in methanol, then given a heat treatment at 410°C in air for 45 minutes. After a water rinse and a mild etch in dilute Br:methanol, Cu doped graphite contacts were applied directly to the CdTe layer. Device fabrication is completed by drying the graphite paste for a few minutes under a heat lamp. The highest NREL confirmed efficiency achieved on a device fabricated in this manner was 9.3% (18.2 mA/cm^2 J_{sc} , 825 mV V_{oc} , and 0.62 FF) on an area of 0.22 cm^2 . See Fig. 5.

2. Oxygen effects

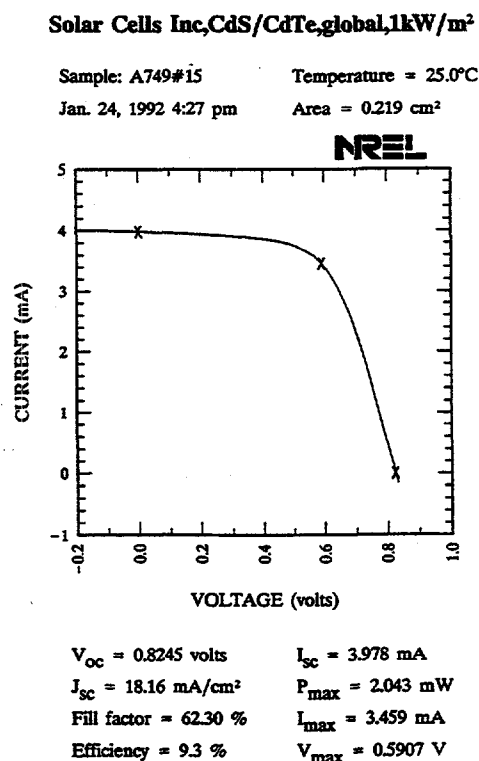
In additional studies, it was observed that oxygen in the deposition chamber has the effect of increasing the V_{oc} of as-deposited two layer films. (Typically we measure V_{oc} using a graphite contact to the CdTe film. Illumination is on a light box designed for viewing 35 mm color slides. Although this light source is not well quantified, this procedure has proven useful for predicting the efficiency of completed devices. Typically the V_{oc} measured on this light box is 100 mV lower than the value obtained under AM1 illumination.)

Two layer devices deposited without oxygen in the deposition ambient typically have a V_{oc} between 200-350 mV. By adding 1 torr O_2 to the deposition ambient, typical V_{oc} increased to the 400-550 mV range. It is emphasized that these measurements were made prior to the CdCl_2 heat treatment. Oxygen treated devices exhibited relatively less response to the CdCl_2 heat treatment and the final efficiencies were similar to those obtained with our routine process. It is possible that oxygen is a shallow acceptor in CdTe, but this has not been confirmed by us. Whatever its role, it is clear that oxygen has a significant effect on film properties. Future studies will explore this effect. As part of this study, we plan to install apparatus to monitor the background level of oxygen in the deposition chamber.

C) Submodules

Interconnected 64 cm^2 aperture area submodules have been produced on 100 cm^2 superstrates. These devices consist of eight cells connected in series. The preferred

FIGURE 5
NREL confirmed cell efficiency results.



interconnect scheme is displayed in Fig. 6. In practice we often used a variation on this procedure in which all semiconductor layers are deposited prior to making the first scribe. Cells are then originally isolated by cutting all of the semiconductor layers, including the $\text{SnO}_2:\text{F}$, with a frequency doubled Nd YAG laser. After this scribe line is filled in with an organic insulator, a channel through the CdTe/CdS films is cut by a second laser scribing operation. A metallic back contact is deposited by e-beam evaporation through a mask. The mask serves to separate individual cells; similar effects can be achieved using laser scribing. At present the highest aperture area efficiency achieved is 7.3% (5.9 V Voc, 130 mA Isc, and 0.61 FF).

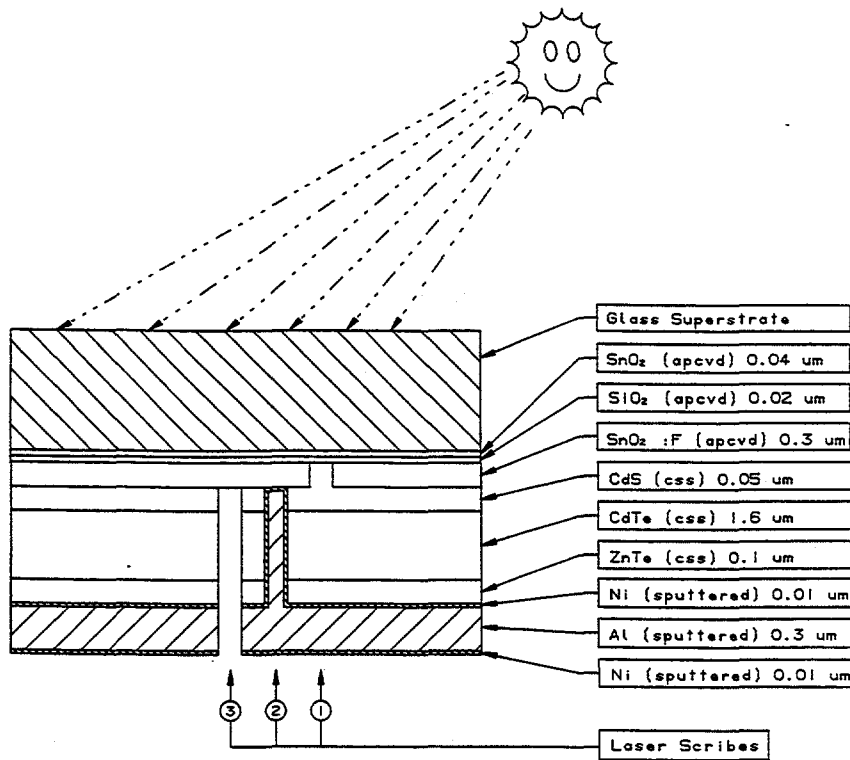


FIGURE 6
Preferred interconnect scheme.

III COMMERCIAL SCALE DEVICES

A) Deposition Apparatus

The LDS (Large Deposition System) incorporates some changes from the RMS which allow it to operate in a more continuous fashion as well as to accommodate the 60 cm X 120 cm superstrates. The change most relevant here is that the source materials are supported above the superstrate such that mass flow is directed downward. See Fig. 7. This allows the glass to be supported on rollers which greatly simplifies transport. As in the RMS, there are zones for preheat, CdS deposition, CdTe deposition, and for ZnTe deposition; the quench, however, is outside of the enclosed area.

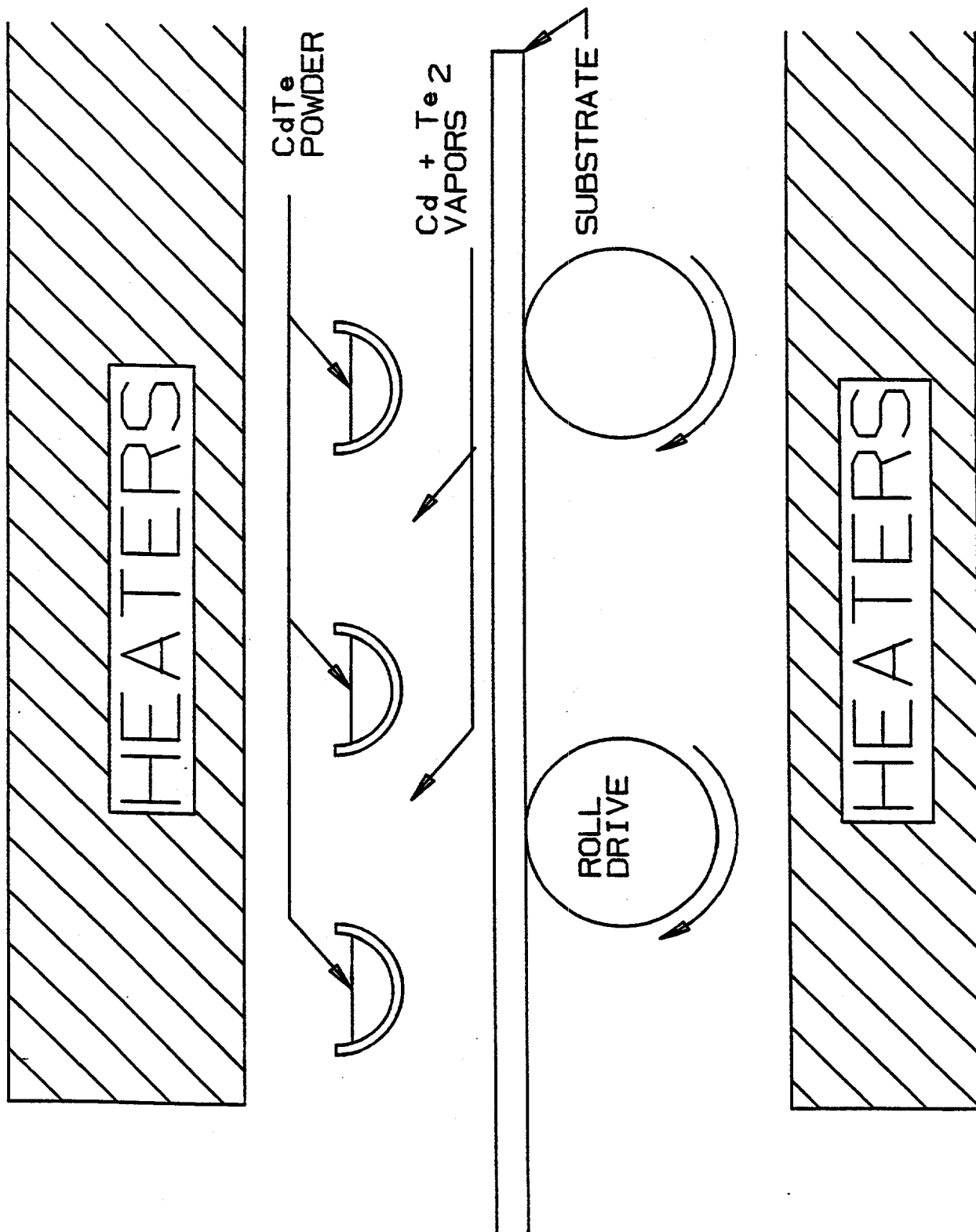


FIGURE 7
Schematic of LDS - Large Deposition Chamber.

B) Semiconductor Deposition

Large area CdS, CdTe, ZnTe, and CdTe/CdS films were deposited in the LDS. Visually, the films appear uniform over the 60 cm X 120 cm surface. Total time to deposit a 2 μm thick film is less than 60 s. The microstructure is similar, although not identical, to that of films deposited in the RMS. Grain size is approximately one micron. As deposited films that were made into cells by simply applying a Cu doped graphite contact produced an efficiency of 2.65% on 1 cm^2 devices (14.9 mA/cm^2 Jsc, 529 mV Voc, and 0.34 FF).

In order to further evaluate the quality of films deposited in the LDS, additional small area devices were produced. Ten centimeter by ten centimeter superstrates were cut from the larger superstrates for further processing. After the CdCl_2 heat treatment and other process steps, device efficiency reached 8.1% (18.5 mA/cm^2 Jsc, 720 mV Voc, and 0.61 FF).

In addition, several submodules were produced using metallic interconnects. Processing including laser scribing for the SnO_2 isolation cuts and for the interconnect channels, and use of evaporation masks for deposition of the metallic back contacts. These devices consist of 8 cells in series with an aperture area of approximately 64 cm^2 . The best devices produced had a Voc of 5.54 V (0.692 V per cell), a total short circuit current of 124 mA, and a FF of 0.51; aperture area efficiency was 5.5%.

C) Modules

During April 1992 we completed construction and assembly of equipment for the fabrication of full size - 60 cm X 120 cm modules. Equipment for semiconductor deposition, metallization, laser scribing, and light I-V testing had been available earlier; equipment for application of CdCl_2 and heat treatment was completed in April. On April 9th SCI produced its first full size module.

Processing was similar to that used for submodules. Deposition was onto a cleaned sheet of 20 Ω/sq SnO_2 coated soda lime glass. Deposition time was approximately 10 s for CdS and 20 s for CdTe. The superstrate temperature was about 600°C during deposition. The CdTe/CdS film received a CdCl_2 heat treatment for 20 minutes at approximately 420°C. Metallization consisted of 200 Å Ni/ 3000 Å Al/ 200 Å Ni - all deposited by sputtering. Laser scribing was used to define the SnO_2 and the metal layers and to cut the interconnect via through the semiconductor films. The module is comprised of 116 cells; each cell is approximately 1 cm X 58 cm.

The AM 1.5 power output was 10 W. The I-V parameters were 47.2 V Voc, 675 mA Isc, and 0.31 FF. Total area efficiency was 1.4%. Clearly there is significant room for improvement. Numerous process steps need to be refined. In fact, the fabrication procedures themselves have not been fully defined. Thus, we can expect that significant improvements will be made in the coming months.

IV CFR (Channel Flow Reactor)

In spite of the successes achieved to date, we believe that improvements can be made in the control of deposition parameters. As deposition is essentially controlled by the thermodynamic conditions existing at the vapor-solid interface, the key to continued improvements

lies in obtaining knowledge and control over mass transport. We have done some numerical modelling of the material transport in our present RMS chambers. The most detailed work in this area has been performed by Ajit Bhat, a graduate student from UT who worked for SCI part time during the summer. This analysis, combined with economic, engineering, and control considerations, confirmed our opinion that we should begin serious consideration of apparatus which provides more complete control of the composition of the source vapors. Thus, a significant effort was spent on the design of a channel flow reactor, CFR.

The equipment designed consists of two independently heated crucibles, each of which contains an elemental source. Thus, for example, one could contain Cd and the other Te. The concept is similar to that developed by Chu et al. [6] and which he called Combination of Vapors of Elements, CVE. In this process a heated carrier gas such as N_2 , Ar, or Ar + H_2 passes over a heated source material. The carrier gas mixes with the elemental vapors and transports them to a superstrate upon which the compound is to be deposited.

The CFR was constructed inside a 25" steel bell jar. It allows us to deposit all three semiconductor films - but only one at a time. The CFR is viewed as an interim deposition chamber; its primary purpose is to provide information on mass transport that will be useful in design of later larger systems. Consistent with this objective, we continue to review and modify the CFR.

In the first design, the CFR was constructed from stainless steel which was then covered with a silica based coating. In spite of the fact that the coating was intended to protect the steel, a severe reaction was observed between the steel crucible and the molten Te. Since then, graphite liners have been designed and built to fit into the steel crucible shells. This eliminated reaction with the crucible walls and enhanced mass transport through the deposition channel.

By collecting condensed Cd and Te vapors at the exit end of the deposition channel, we found that the ratio of the measured mass of material transported through the channel to the calculated mass of saturated carrier gas is approximately 1:3. See Fig. 8. The apparent discrepancy, i.e., the loss of material, can be ascribed primarily to two factors: 1) the measured amount of material in the channel is lower than the actual amount transported, and 2) the actual concentration of source material in the vapor phase in the crucibles is lower than the theoretical value. It should be noted that material utilization efficiency is significantly lower than this ratio. This is because the amount of material transported is measured at the outlet of the CFR - not on the glass superstrate. These measurements were made primarily with one source at a time, i.e., either Cd or Te, under conditions for which deposition of CdTe on the superstrate was neither observed nor expected.

CdTe was deposited for the first time in the CFR during March. Depositions were performed with a background pressure of 100 torr Ar with 2% H_2 . Gas flow rate was ~0.5 lpm (this translates to a carrier velocity of ~2 cm/s). The glass temperature was approximately 550°C. The precise amount of material deposited has not been determined, but it is estimated that 15-30 mg of Cd passed over the sample during the deposition process and that less than 2 mg of CdTe (i.e, less than 1 mg of Cd) was deposited on the glass. Although this suggests a very low material utilization efficiency, it is emphasized that these numbers are not well established and require refinement.

Mass Transport of Cd in CFR

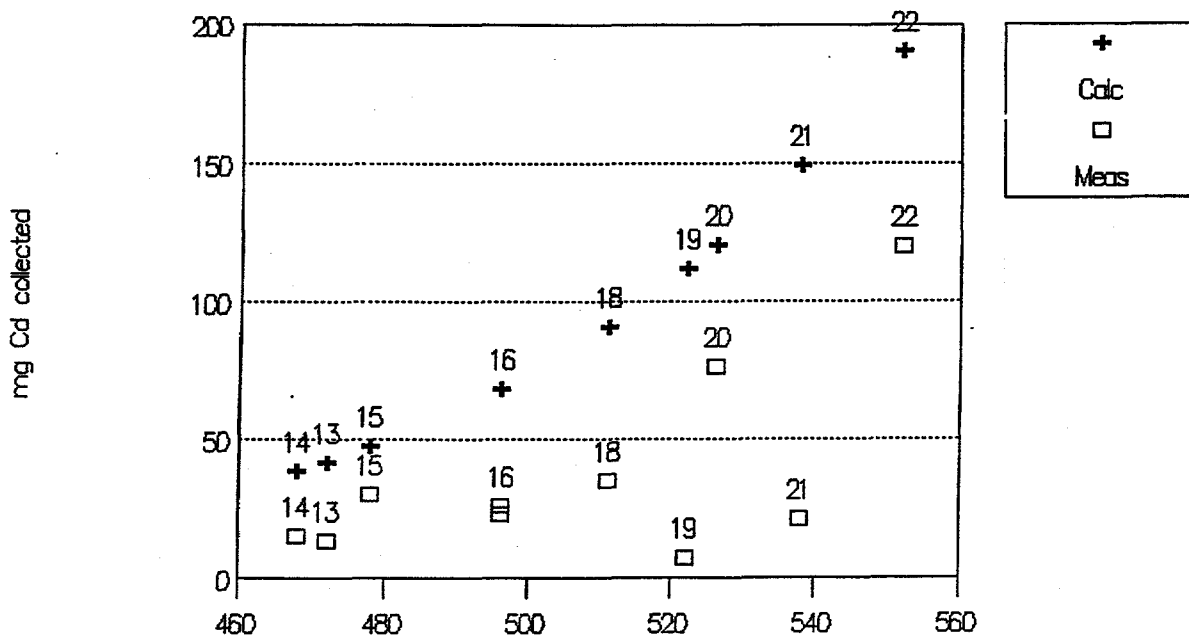


FIGURE 8

Mass Transport in CFR. Calculated values (+) are approximately 3X measured amounts (□).

Further depositions were performed at atmospheric pressure in the Ar -2% H₂ ambient. These films were also spatially non-uniform in composition and thickness - Te nodules were observed on some films. Channel temperatures were increased in an attempt to eliminate the Te deposition, but heater failure occurred. It has been decided to refit the original CFR apparatus with new heaters, but in addition to design and construct a more durable version. This work is underway.

V Safety, Health, Environment and Disposal

Safety and health of workers, environmental control of the production process, and disposal of product at the end of its useful life are major considerations in any manufacturing program. In the case of CdTe-based photovoltaics, this concern is highlighted due to the use of cadmium bearing materials. From its inception, SCI has pursued a vigorous policy of strictly monitoring and protecting employee safety and health.

Analysis of the urine is believed to be a reliable indicator of long term exposure to Cd. Prior to exposure to any Cd-bearing materials, all employees were given a complete physical including a urine analysis which tested for Cd. This is followed up by urine analyses on every employee at six month intervals.

As the primary route of entry of Cd into the human body is through the lungs, SCI's

program includes measurements to determine the levels of Cd and other materials to which workers are exposed in the SCI workplace. Air sampling studies were performed by FOHC - an industrial hygiene and environmental services company. At the very beginning of the program, air samples were taken during loading and unloading of the source boats and during cleaning of the chamber and of the deposition apparatus. At no time did the level of airborne Cd reach the OSHA PEL (Personal Exposure Limit) of 200 ug/m³. It should be noted that, although the duration of each operation monitored was about 1/2 hour and is typically performed one time per week, the OSHA PEL's are based on a time weighted average over a 40 hr week. Thus, these results would suggest that ordinary safe practices to be followed in the handling of any chemical would be sufficient for working with the CdS and CdTe compounds employed at SCI. Every precaution is taken, however, to protect workers while tests continue with the monitoring of continually updated procedures.

Likewise, airborne cadmium continues to be monitored periodically in work, laboratory and office spaces. In no case have airborne Cd levels been determined to exceed OSHA standards. As an additional precaution, however, personnel wear lab coats, gloves and goggles for certain operations. No SCI worker has tested above the background level for Cd.

In order to determine the amount of Cd-bearing compounds released into the environment, air exhausted from the deposition chambers is monitored for Cd compounds. In spite of the relatively high vapor pressures existing within the chambers, there is no evidence of Cd compounds in the pump exhausts or in the mechanical pump oil.

Regarding disposal of spent modules, active discussions are proceeding between SCI and its suppliers. It is not yet known whether spent modules will have to be treated as toxic waste or whether they can simply be placed into landfills. In any case, it is hoped that spent modules will not have to be discarded, but rather can be recycled.

VI SUMMARY

A) Status

During the first year of the subcontract, SCI has developed and demonstrated innovative equipment and procedures for deposition of CdTe, CdS, and ZnTe films using apparatus readily adaptable to a manufacturing environment. This includes the design, construction and operation of three separate deposition systems - the RMS, LDS, and CFR - for research scale, full scale, and advanced designs, respectively. Efficiency result obtained are:

Device	Area	Efficiency
Cell	.02 cm ²	9.3%
Submodules	64 cm ²	7.3%
Modules	7200 cm ²	1.4%

In addition, an active safety, health, environmental and disposal program has been instituted.

B) Further Work

During the first year of the contract, emphasis was placed on putting together equipment, making depositions, and demonstrating proof of concept results. During the next two years of the contract increased emphasis will be placed on refining our control of deposition procedures and on the understanding of material and device properties.

We anticipate increased emphasis on development of improved procedures in the mechanics of module fabrication - cleaning, laser scribing, semiconductor deposition in the LDS, metallization, lead attachment, and encapsulation. In addition, however, we will bring on line our in-house analytical system. This will allow us to perform conductivity, photoconductivity, and optical transmission measurements on films and to perform spectral response, dark I-V vs T, C-V, and C-f measurements on devices. In addition we anticipate increased cooperation with researchers at NREL in the utilization of photoluminescence, Auger, ESCA, ebic, and TEM. In addition, we will spend more time on understanding the mass transport and high temperature chemistry involved with a detailed control of CVE and of doping of ZnTe films.

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16. Abstract (Limit: 200 words) This report describes work to produce 60 cm x 120 cm solar power modules based on thin-film CdTe. The method of choice for semiconductor deposition is condensation from high-temperature vapors. Early work focused on close-spaced sublimation and chemical vapor deposition using elemental sources. Small-area conversion efficiency was confirmed by NREL at 9.3% on a 0.22-cm ² device ($V_{oc} = 825$ mV, $J_{sc} = 18.2$ mA/cm ² , and $FF = 0.62$) deposited on a 100-cm ² substrate. On 8 cells, (64 cm ² submodules), the best result to date is 7.3% ($V_{oc} = 5.9$ V, $I_{sc} = 130$ mA, and $FF = 0.61$). CdS, CdTe, and ZnTe films were deposited onto 60 cm x 120 cm substrates; single cells produced from this material exceeded 8% efficiency, and 64-cm ² submodules exceeded 5%. Module efficiency is limited by mechanical defects (mostly shunts) associated with processing after the semiconductor layers are deposited. The present best result is 1.4% total-area efficiency with a power output of 10 W. Further optimization should improve the performance of the modules.			
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